

Search for Sterile Neutrinos Using the MiniBooNE Beam

Michel Sorel, Columbia University

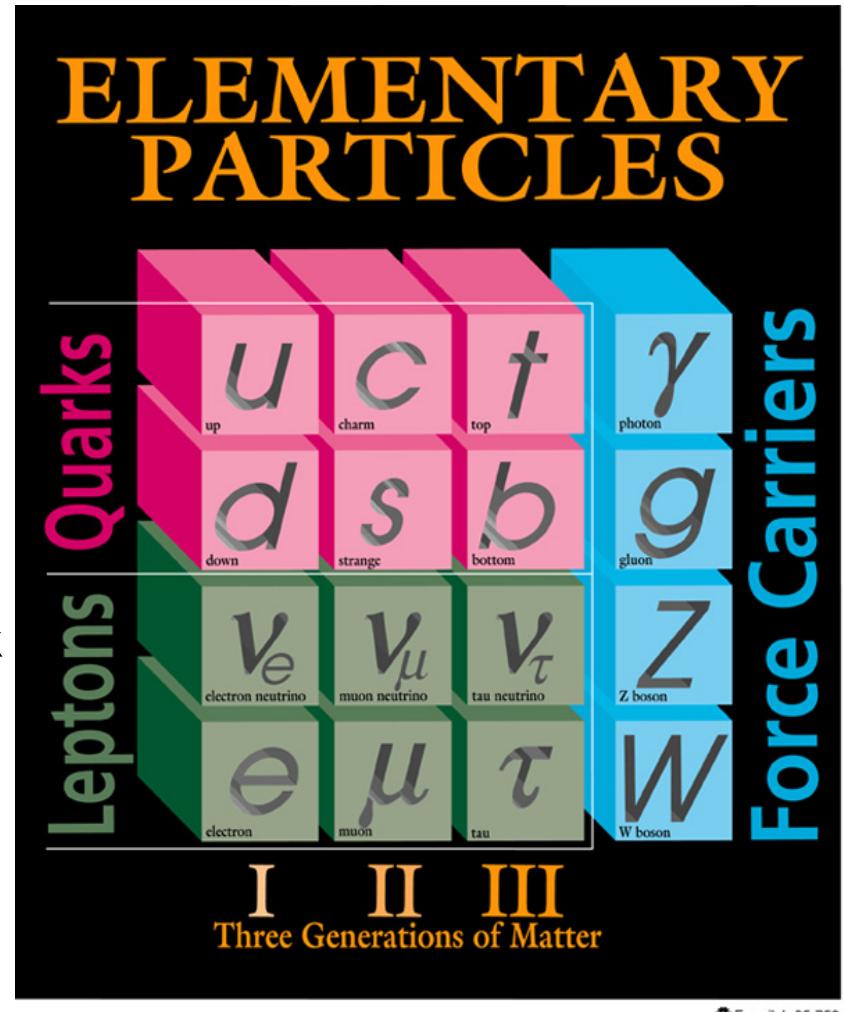
Dissertation Sponsor: Prof. Janet Conrad

- Sterile Neutrinos and Neutrino Oscillations
- MiniBooNE Beam and Detector
- $\nu_\mu n \rightarrow \mu^- p$ Interactions
- Muon Neutrino Disappearance Search

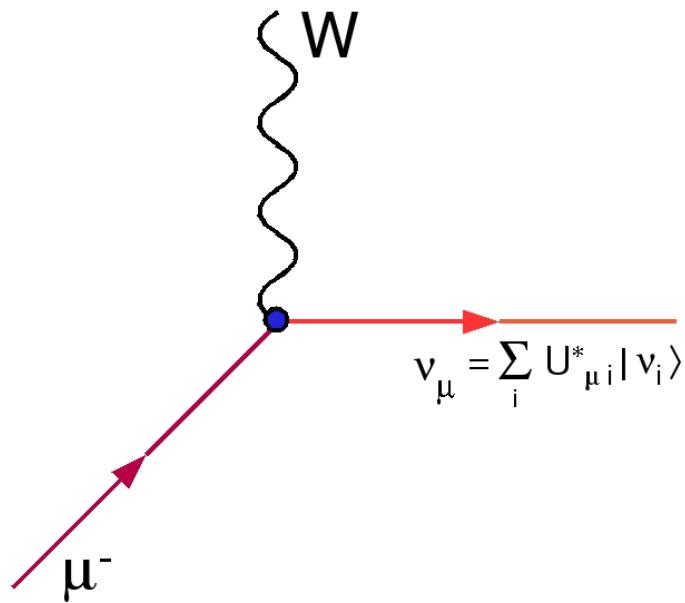
New York
March, 2005

Neutrinos: What We Know

- Lightest known fermions
- No color (no QCD interactions)
- No charge (no EM interactions)
- Only weak interactions
- Three light “active” neutrino families
- Paired with charged leptons in weak isodoublets
- Non-zero masses and mixings



Neutrino Mixing



Flavor eigenstates $|\nu_\alpha\rangle$ ($\alpha = e, \mu, \tau$):

- Identified with charged lepton:
Produced in decay with lepton l_α^+
Produces lepton l_α^- in CC interaction

Mass eigenstates $|\nu_i\rangle$:

- Determines free particle evolution
Solutions to Schrödinger's Equation
 $|\nu_i(\mathbf{x})\rangle = e^{-i\mathbf{p}\cdot\mathbf{x}} |\nu_i(\mathbf{0})\rangle$

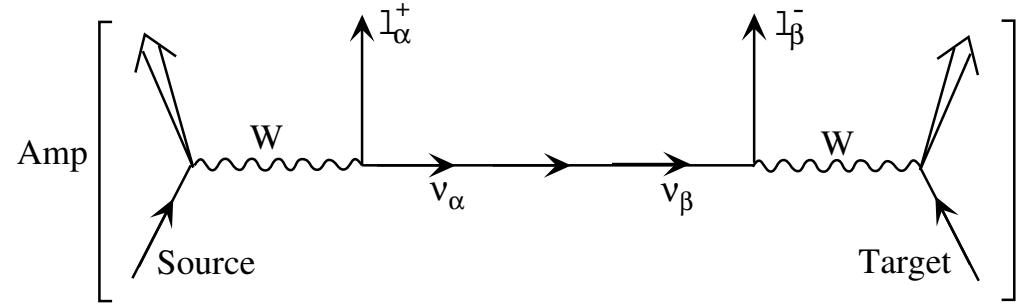
Flavor/mass eigenstates related by unitary MNS mixing matrix U :

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

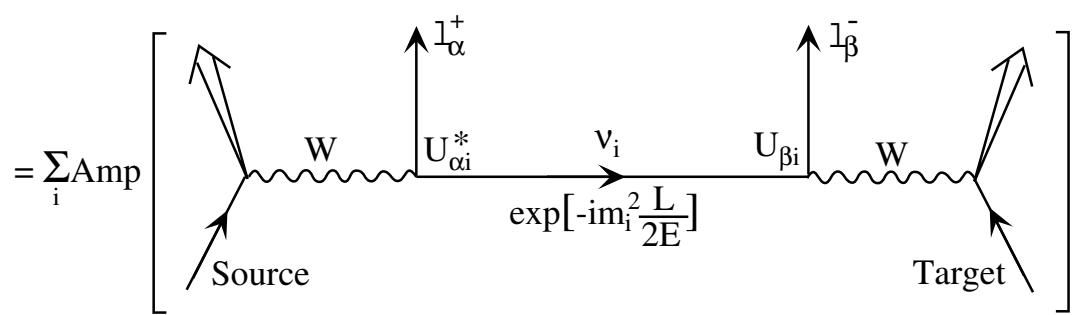
Mass splittings and mixings determined experimentally via neutrino oscillations

Neutrino Oscillations

- **Appearance:** start with flavor α and observe different flavor β after some time/distance



- **Disappearance:** start with known amount of ν_α , find less ν_α later



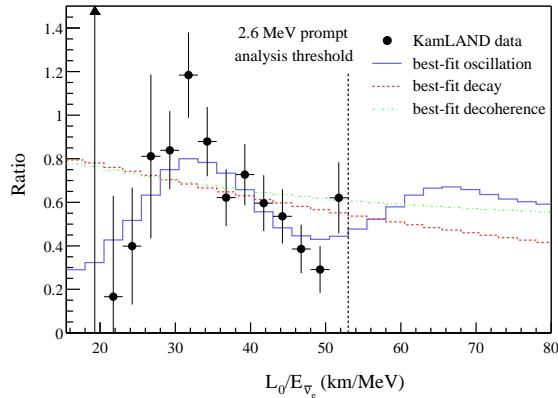
- Oscillation probability:

$$\begin{aligned} P(\nu_\alpha \rightarrow \nu_\beta) = & \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2[1.27 \Delta m_{ij}^2 (L/E)] \\ & + 2 \sum_{i>j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin[2.54 \Delta m_{ij}^2 (L/E)] \end{aligned}$$

- $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$

- Non-zero and non-degenerate masses, $U \neq 1 \Rightarrow$ neutrino oscillations

Experimental Evidence for Neutrino Oscillations

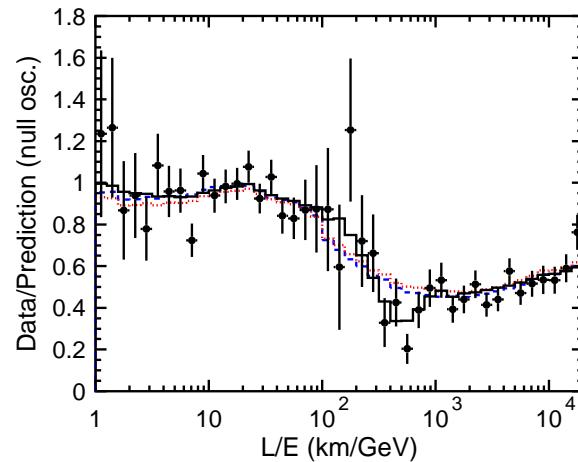


Solar Neutrino Oscillations

- Deficit of ν_e observed from Sun
Cl (Homestake), H₂O ((Super-)K), Ga (GALLEX, SAGE)
- Confirmation at SNO and KamLAND (reactor $\bar{\nu}_e$)

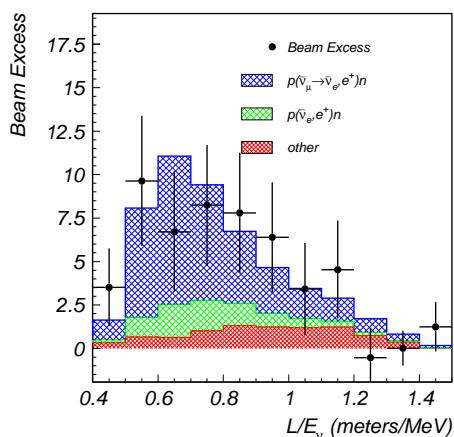
Atmospheric Neutrino Oscillations

- Zenith angle-dependent deficit of ν_μ :
Kamioka, Super-Kamiokande, Soudan, MACRO
- Confirmed by accelerator exp K2K; MINOS will be definitive



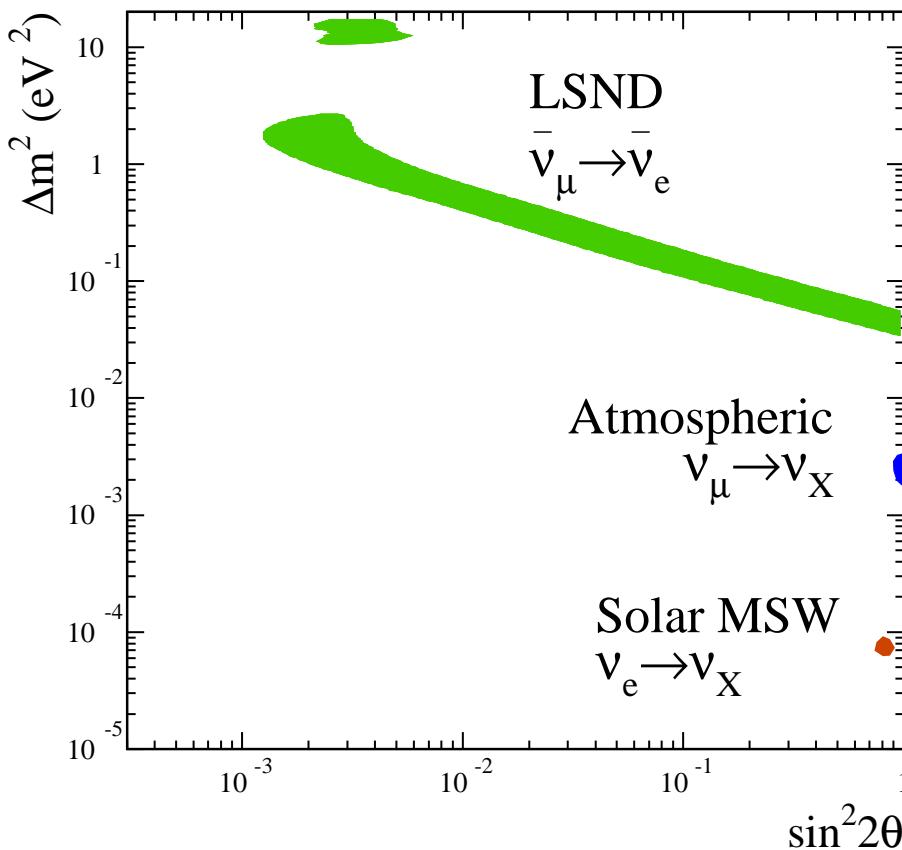
LSND Neutrino Oscillations

- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam produced from μ^+ decay-at-rest
- Unconfirmed by other experiments, but not excluded



Two-flavor Oscillation Parameters

- All individual experimental evidences can be described by a single mass splitting Δm^2 and a single mixing parameter $\sin^2 2\theta$:

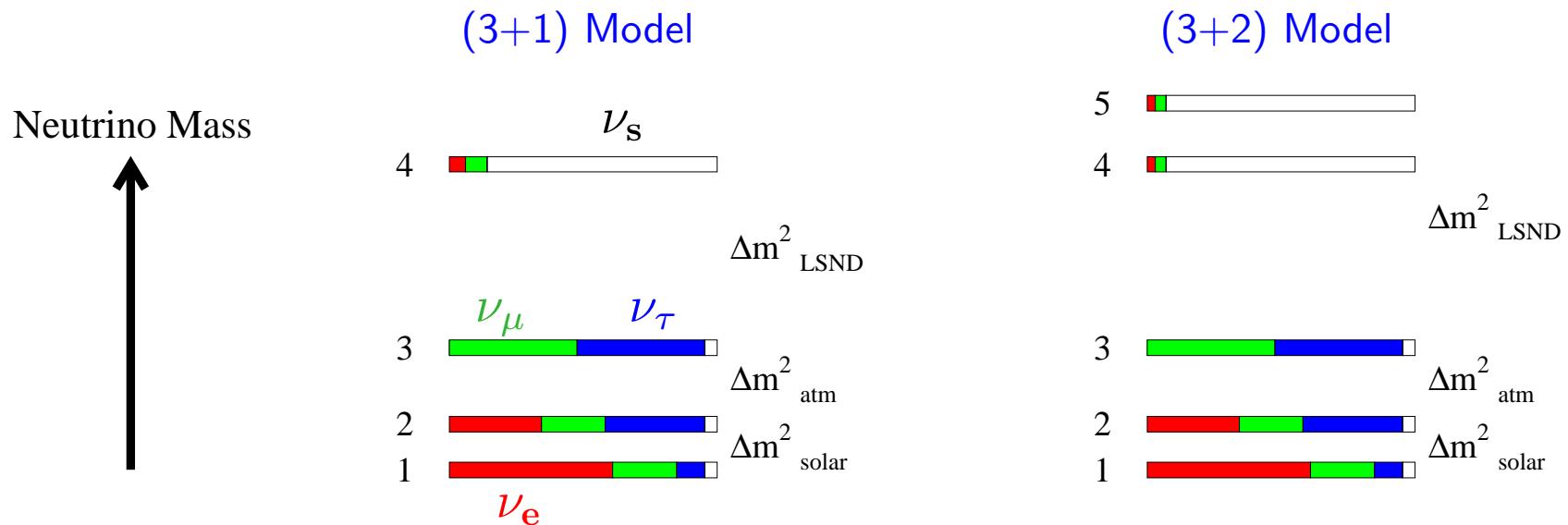


- $P(\nu_\alpha \rightarrow \nu_{\beta \neq \alpha}) = \sin^2 2\theta_{\alpha\beta} \sin^2[1.27\Delta m^2(L/E)]$
- $P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2[1.27\Delta m^2(L/E)]$
- LSND:
 $\Delta m^2 \approx 0.1 - 10 \text{ eV}^2$, small mixing
- Atmospheric:
 $\Delta m^2 \approx 2 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta \approx 1.0$
- Solar:
 $\Delta m^2 \approx 7 \times 10^{-5} \text{ eV}^2$, $\sin^2 2\theta \approx 0.8$

- Three distinct neutrino oscillation signals, with: $\Delta m^2_{\text{LSND}} \gg \Delta m^2_{\text{atm}} \gg \Delta m^2_{\text{sol}}$

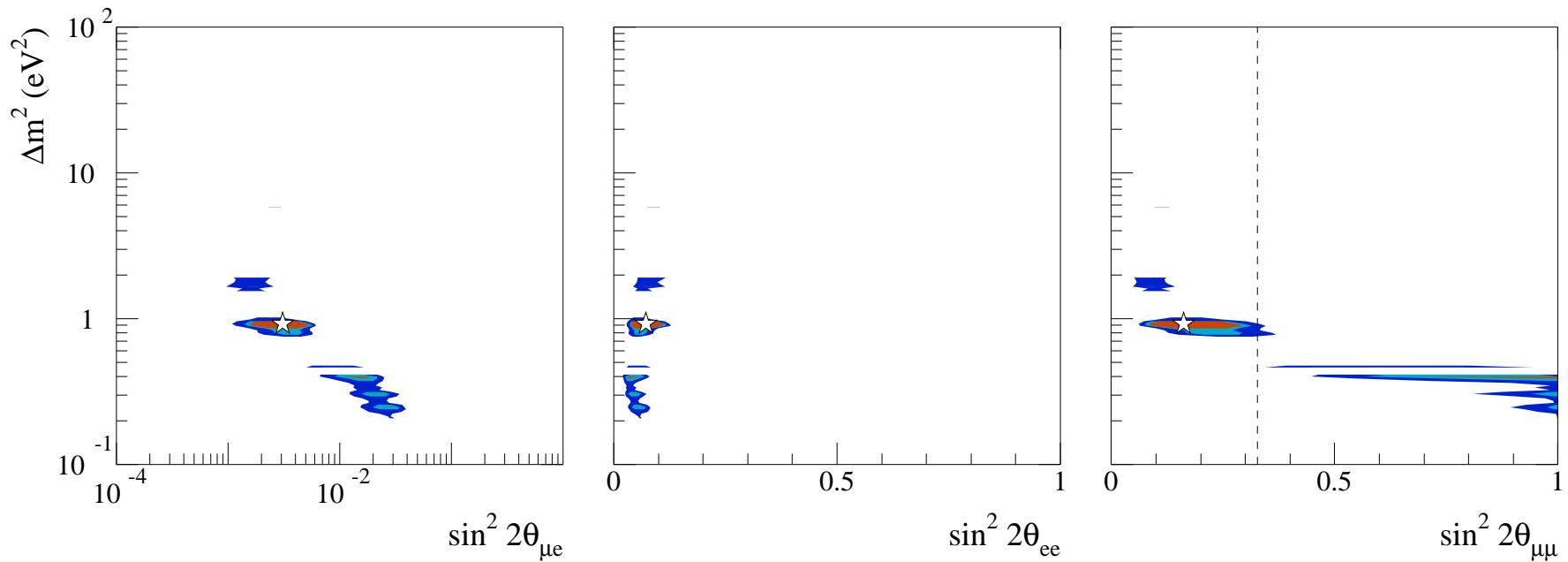
Sterile Neutrinos

- Sterile neutrinos: neutrinos with no weak couplings. In standard electroweak theory, sterile neutrinos are right-handed particles.
- Sterile neutrinos are required by the see-saw mechanism generating neutrino masses
- Neutrino oscillations among active flavors only cannot explain three independent Δm^2 , because only three light, active neutrino species are known to exist from $e^+e^- \rightarrow Z^0$ measurements at LEP
- Active-active plus active-sterile neutrino oscillations allow for three (or more) independent Δm^2 , accommodating solar, atmospheric, and LSND oscillations



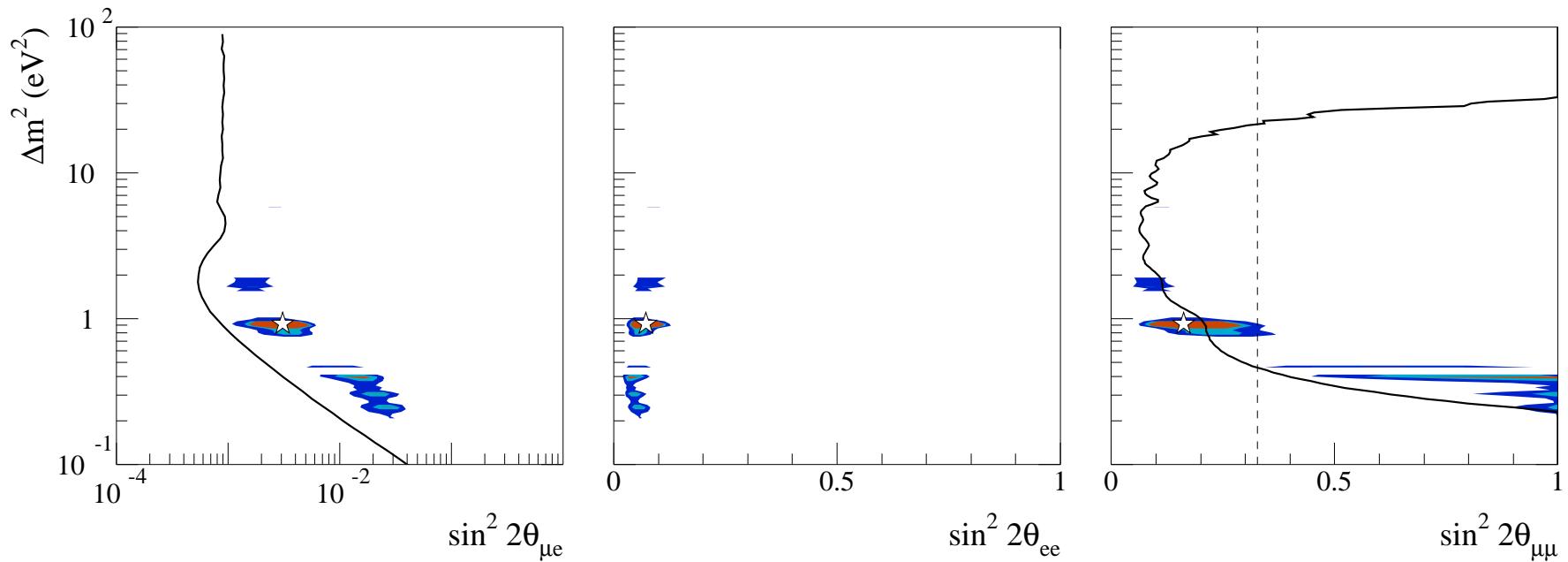
Expectations for Active-Sterile Neutrino Oscillations

- Combined analysis of $\nu_\mu \rightarrow \nu_e$, $\nu_e \rightarrow \nu_\phi$, $\nu_\mu \rightarrow \nu_\mu$ oscillation searches, assuming a (3+1) sterile neutrino model, point to following neutrino masses and mixings (MS, J. Conrad, M. Shaevitz, PRD **70**:073004):



Expectations for Active-Sterile Neutrino Oscillations

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- Solid lines show MiniBooNE sensitivity to $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\mu$ oscillations
⇒ “guaranteed” discovery, if LSND due to active-sterile neutrino oscillations!
- Similarly, mixings that are large enough to be observable at MiniBooNE are expected in the favored (3+2) sterile neutrino models, for $0.2 \lesssim \Delta m^2 \lesssim 50$ eV 2

Neutrinos: Open Questions

Issues	Questions	Theorists' Poll*
# of Light Neutrinos	3 active + ? steriles	Three
Majorana vs Dirac	$\nu = \bar{\nu}$, 2 vs 4 states per ν , L viol.	Majorana
Masses	degenerate, normal/inverted	See-saw
Mixings	$\theta_{13}, \theta_{23} \stackrel{?}{=} \pi/4$, U real vs complex, CP Violation , Leptogenesis	???
Exotics	Non-osc., CPT-V, decays, μ -mom, etc.	None

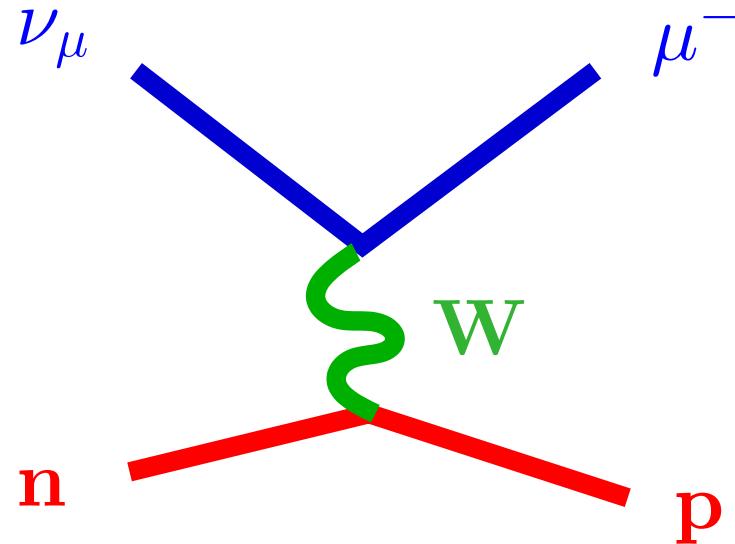
* From S.Parke, FNAL, Nov 2003: “At least one theoretical prejudice is wrong”

- **Marked in blue:** studied in the context of sterile neutrino models

Search for Sterile Neutrinos via $\nu_\mu n \rightarrow \mu^- p$ Interactions

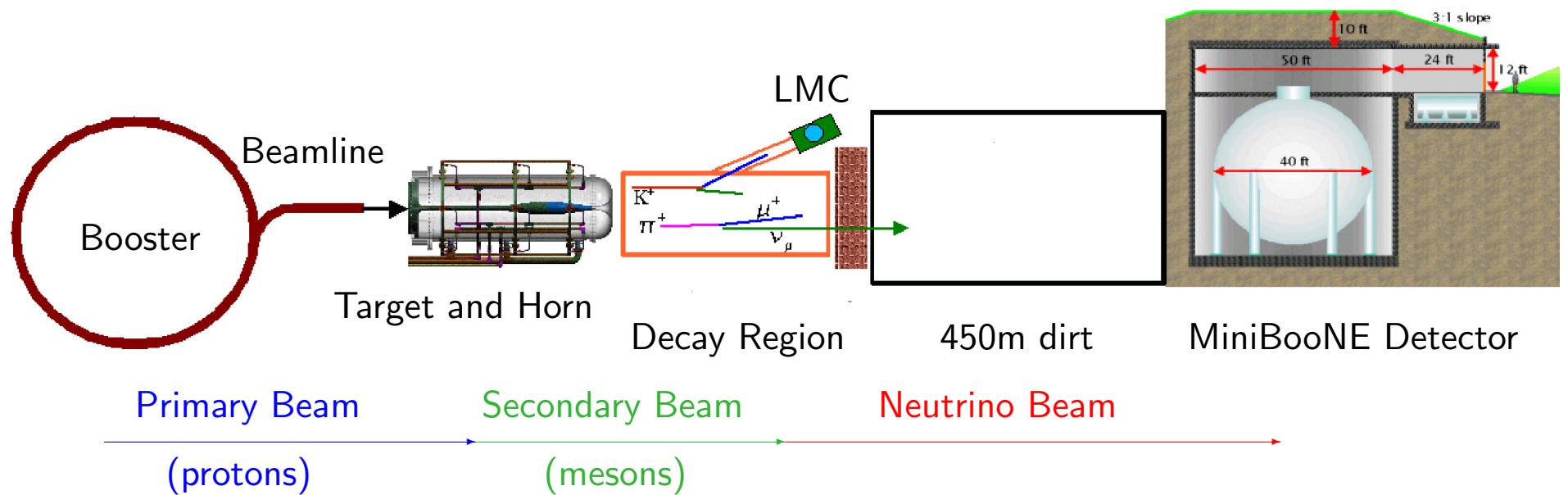
- if $\nu_\mu \rightarrow \nu_s$ oscillations are present between neutrino production and detection, fewer muon neutrino interactions than expected would occur at MiniBooNE
- Oscillation probability depends on neutrino energy, therefore **three** types of muon neutrino disappearance analyses are possible:
 - **normalization-only:** compare overall number of interactions with expectations
 - **shape-only:** look for neutrino energy-dependent distortions in the observed spectrum, compared to expectations (analysis discussed here)
 - **normalization plus shape:** combine both informations

Search for Sterile Neutrinos via $\nu_\mu n \rightarrow \mu^- p$ Interactions (2)



- This analysis uses a sample of **charged-current, quasi-elastic muon neutrino interactions** (CCQE, $\nu_\mu n \rightarrow \mu^- p$) for the disappearance search, because:
 - 2-body kinematics of the reaction allow for the best possible **neutrino energy reconstruction**
 - disappearance analysis in single-detector experiment relies on external neutrino flux and cross-section predictions. The **best-known neutrino process** in the $\simeq 1$ GeV energy range is the CCQE interaction

MiniBooNE Neutrino Beam



Primary Beam: 8 Gev protons from Booster, $8 \cdot 10^{-6}$ duty factor

Secondary Beam: mesons are produced from protons striking Be target, focused by horn, and monitored by “Little Muon Counters” (LMC)

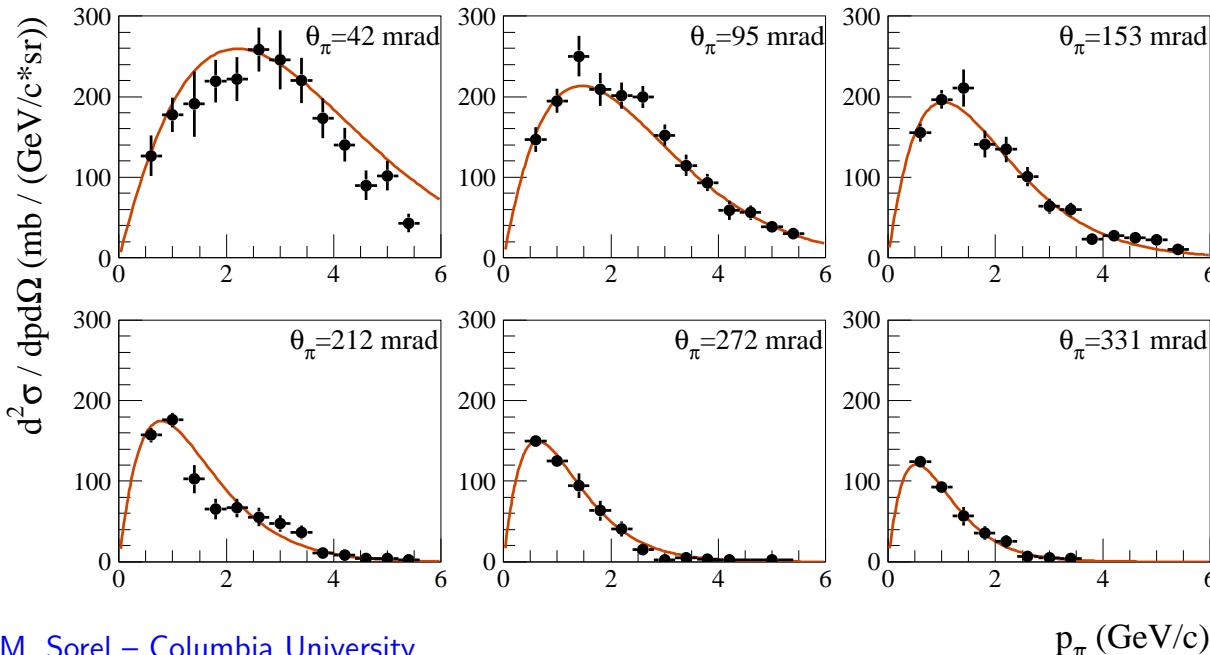
Neutrino Beam: neutrinos from meson decay in 50m pipe, pass through 450m of dirt (and oscillate?) to reach MiniBooNE detector

Neutrino Flux Simulation

- GEANT4 description of the beamline to simulate:
 - primary protons, geometry, materials and magnetic field in target hall and decay region;
 - physics processes governing interactions/focusing/decays of baryons, mesons, and muons.
- Most neutrinos from $\pi^+ \rightarrow \mu^+ \nu_\mu$. Flux uncertainty dominated by uncertainty on $p + Be \rightarrow \pi^+ + X$, described via Sanford-Wang parametrization:

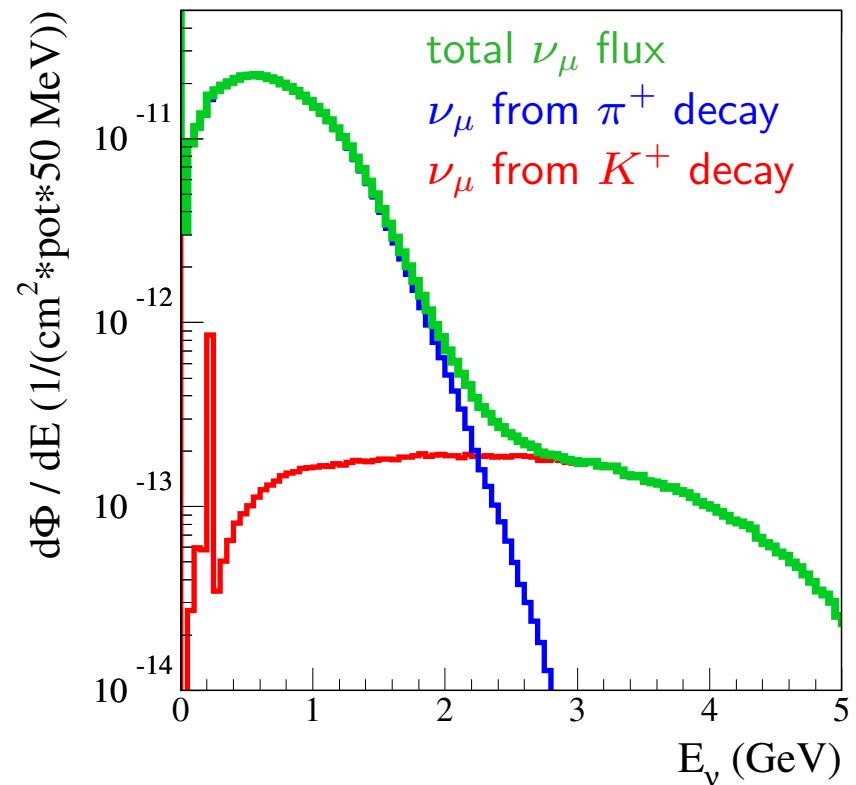
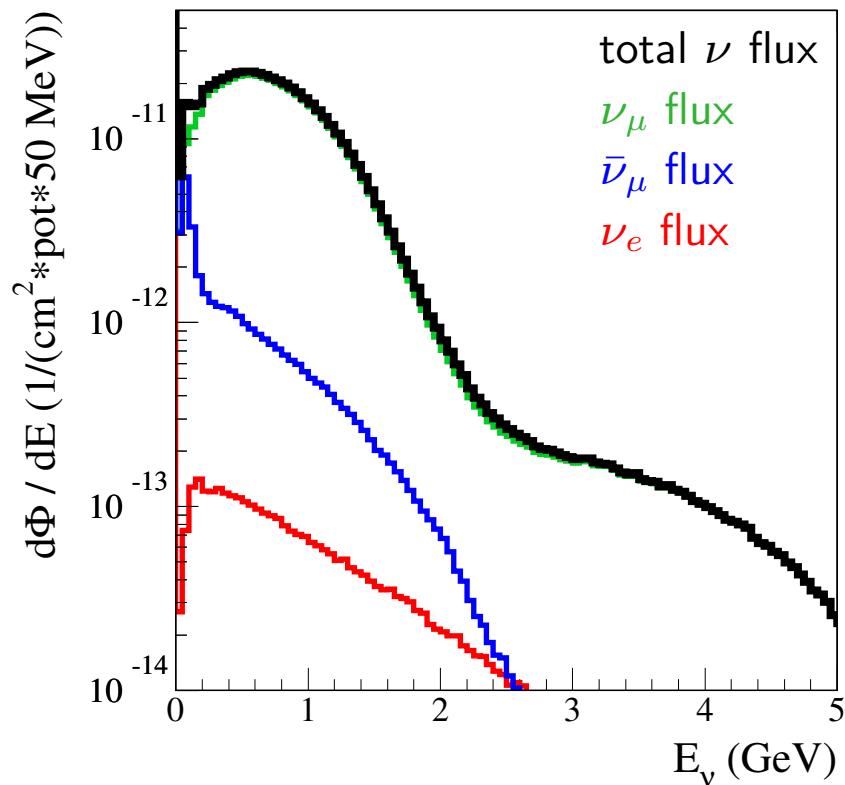
$$\frac{d^2\sigma(p + Be \rightarrow \pi^+ + X)}{dp d\Omega} = c_1 p^{c_2} \left(1 - \frac{p}{p_{beam} - c_9}\right) \exp\left[-c_3 \frac{p^{c_4}}{p_{beam}^{c_5}} - c_6 \vartheta(p - c_7 p_{beam} \cos^{c_8} \vartheta)\right]$$

- Constrain flux predictions by using existing π/K production data (\Rightarrow BNL E910) as inputs to simulation. Plan to use CERN HARP measurements when available



BNL E910 $p + Be \rightarrow \pi^+ + X$ data at
 $p_{beam} = 12.3$ GeV/c, compared to
 Sanford-Wang parametrization in G4

Neutrino Flux Predictions



Neutrino Flavor	Neutrino Parent	Flux ($cm^{-2} pot^{-1}$)	Flux Fract. (%)	$\langle E_\nu \rangle$ (GeV)
all	all	$5.2 \cdot 10^{-10}$	100.0	0.76
ν_μ	all	$4.8 \cdot 10^{-10}$	92.7	0.78
ν_μ	π^+	$4.7 \cdot 10^{-10}$	89.8	0.73
ν_μ	K^+	$1.4 \cdot 10^{-11}$	2.7	2.25
$\bar{\nu}_\mu$	all	$3.5 \cdot 10^{-11}$	6.6	0.49
ν_e	all	$3.1 \cdot 10^{-12}$	0.6	0.94

Neutrino CCQE Cross-Section Predictions

- Neutrino cross-section predictions via NUANCE simulation. Given the MiniBooNE flux, about **40% of all interactions** are expected to be CCQE: $\nu_\mu n \rightarrow \mu^- p$
- Free nucleon CCQE cross-section is described by Llewellyn-Smith formalism:

$$\frac{d\sigma}{dQ^2} = \frac{m_N^2 G_F^2 |V_{ud}|^2}{8\pi(\hbar c)^4 E_\nu^2} [A(Q^2) + B(Q^2) \frac{(s-u)}{m_N^2} + \frac{C(Q^2)(s-u)^2}{m_N^4}]$$

$Q^2 \equiv -(p_\nu - p_\mu)^2$, $(s-u) \simeq 4m_N E_\nu - Q^2$, and A , B , C depend on form factors describing the weak hadronic current, parametrized via vector and axial masses

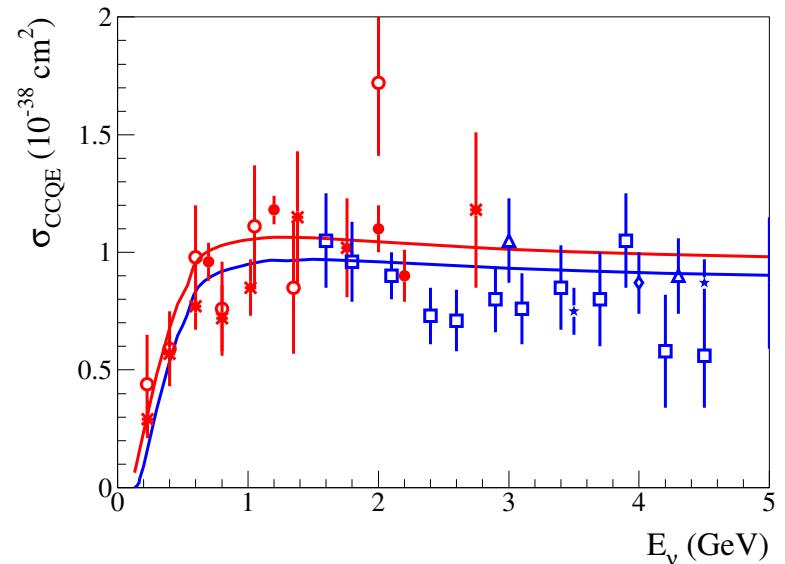
- Target neutrons bound in Carbon nuclei \Rightarrow nuclear effects, in the form of Pauli suppression, Fermi momentum, and final state interactions, are taken into account

Curve: free nucleon NUANCE prediction ($m_A = 1.03$ GeV)

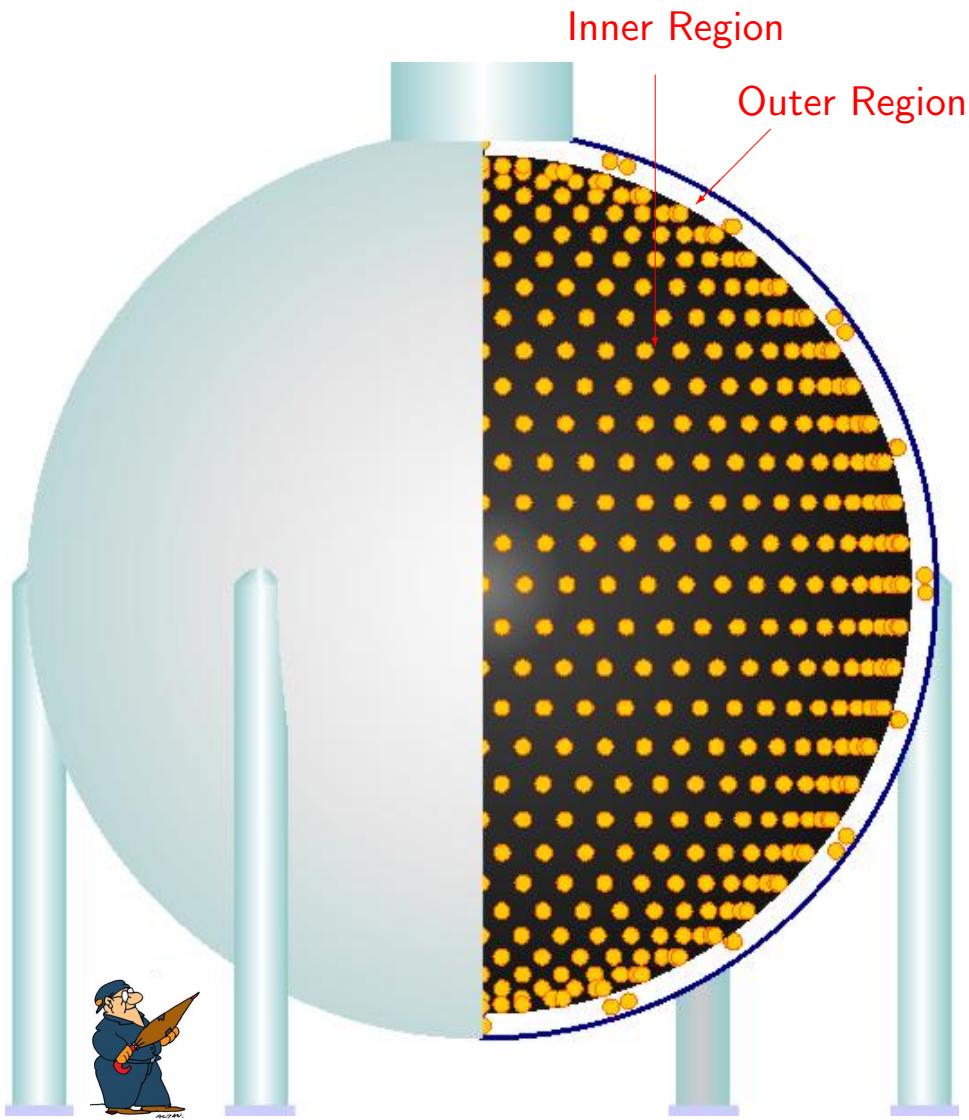
Points: CCQE data on deuterium targets

Curve: bound nucleon NUANCE prediction, with Fermi gas nuclear model ($E_B = 25$ MeV, $p_F = 220$ MeV/c)

Points: CCQE data on heavier targets

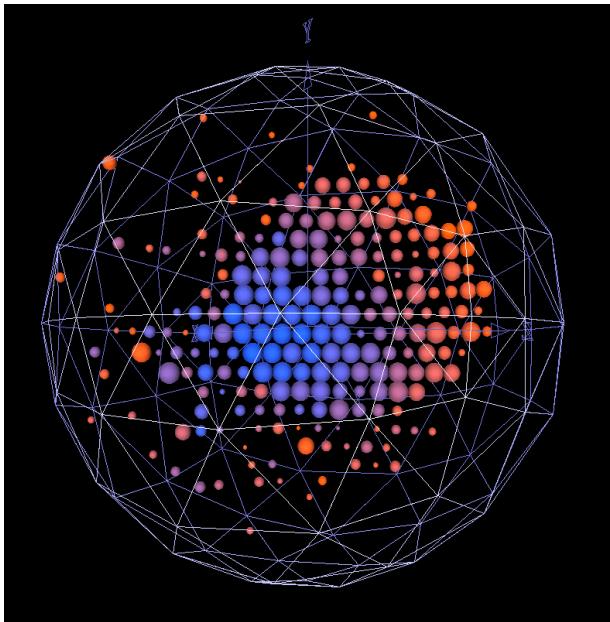


MiniBooNE Detector



- 12m in diameter sphere filled with 800t of undoped mineral oil
- Light tight inner region with 1280 8" PMTs (10% coverage)
- 240 PMTs in outer region (>99% veto efficiency)
- Neutrino interactions in oil produce:
 - Prompt, ring-distributed Cherenkov light
 - Delayed, isotropic scintillation light
- Light transmission affected by: fluorescence, scattering, absorption

Event Reconstruction and Particle ID



- Measure photoelectrons from optical photons reaching the PMT surface:
 - total charge
 - spatial distribution
 - time distribution

- **Event Reconstruction:**

- correlated electrons from muon decays
- neutrino interaction vertex
- direction, spatial extent, and energy of Cherenkov tracks (e, μ, π^0)
- separate amounts of Cherenkov and scintillation light;
- for CCQE events, full event kinematics: neutrino energy, Q^2 , etc.

- **Particle ID:** distinguish $e/\mu/\pi^0$

Calibration Samples

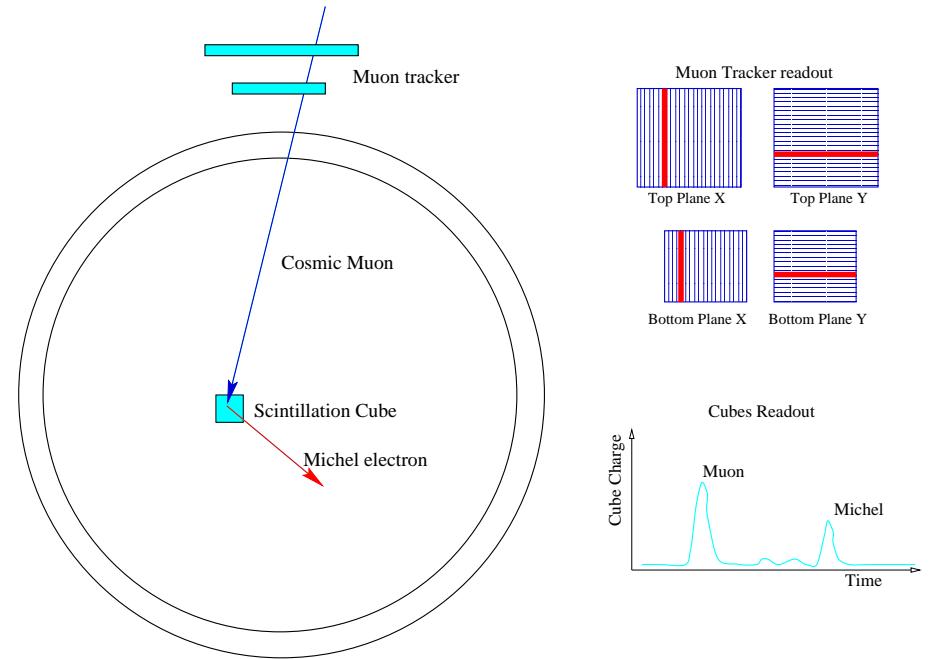
Laser Calibration Sample: prompt, isotropic laser light source

- PMT hit reconstruction: PMT time/charge resolution, pre/afterpulsing
- Oil optical properties: absorption, surface reflections, scattering

Muon Calibration Sample:

cosmic rays through tracker, and stopping in scintillation cubes

- Muons of known direction, decay vertex, pathlength
- Provides independent measurement of muon energy up to 700 MeV



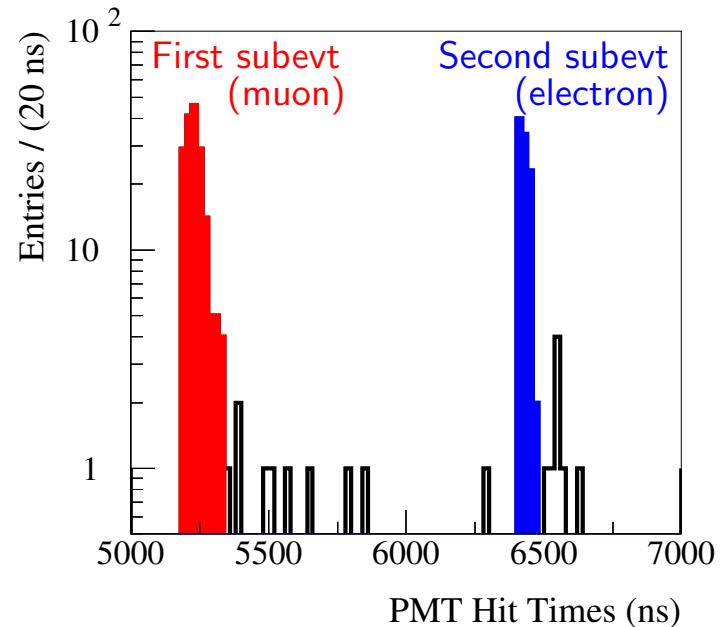
Electron Calibration Sample: Michel electrons from muon decays at rest

- Known energy spectrum between 0 and 52.3 MeV \Rightarrow fix energy scale
- Energy reconstruction accuracy: 14% at 52.3 MeV

CCQE Event Selection Procedure

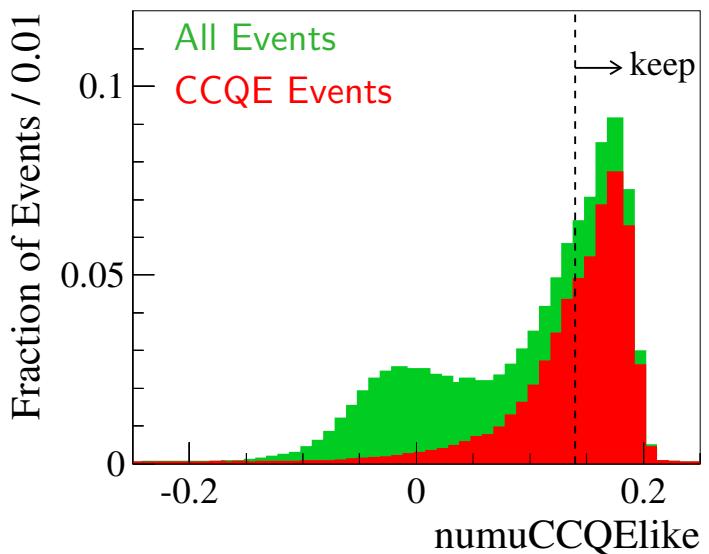
Hit-level and reconstruction-level selection:

- one or two subevents ($\Rightarrow \leq 1$ decay electrons);
- low veto activity, and at least 100 PMT hits in main detector region ($E_{\text{vis}} \gtrsim 50$ MeV);
- mean light emission time within beam spill;
- successful reconstruction, and mean light emission point within fiducial volume ($R < 500$ cm).



Event-level selection:

- Use ten reconstructed quantities as inputs to Fisher discriminant method;
- Quantities related to coarse and fine hit timing structure, and to spatial topology of detected light;
- Algorithm tuned on simulated data to isolate events with a single, muon-like Cherenkov ring, and scintillation light consistent with $\nu_\mu n \rightarrow \mu^- p$.

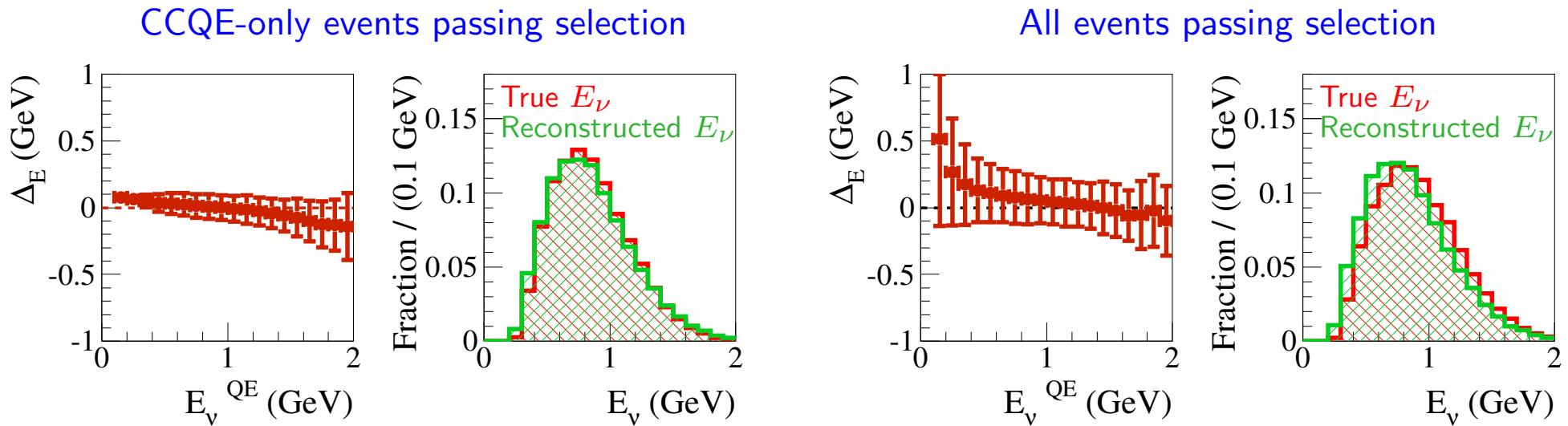


Neutrino Energy Reconstruction

- Obtained from muon energy E_μ and direction θ_μ , via 2-body kinematics:

$$E_\nu^{\text{QE}} = \frac{1}{2} \frac{2(m_N - E_B)E_\mu + (2m_N E_B - m_\mu^2 + E_B^2)}{(m_N - E_B) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2} \cos \theta_\mu}$$

- Muon and neutrino energy calibrated via simulated data
- $\Delta_E \equiv \text{Mean}[E_\nu^{\text{gen}} - E_\nu^{\text{QE}}] \pm \text{RMS}[E_\nu^{\text{gen}} - E_\nu^{\text{QE}}]$ describes biases and resolution

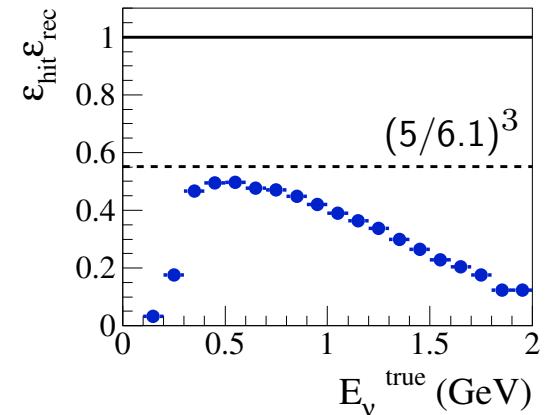


- Expect 11% (30%) resolution for CCQE-only events (all events) passing selection

Expected Performance of the CCQE Event Selection

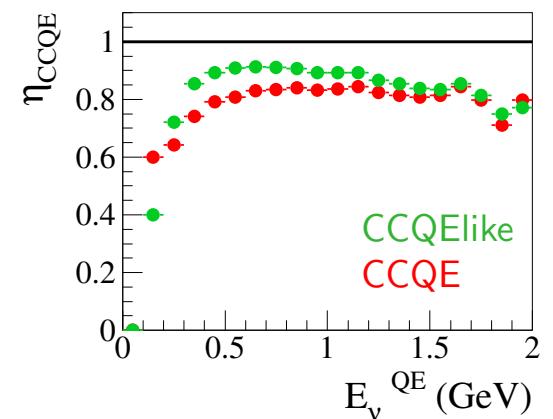
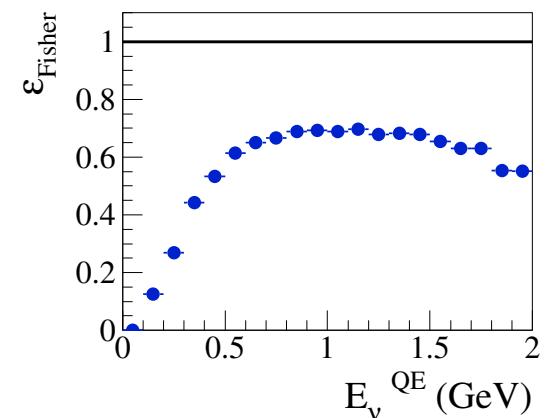
Hit-level and reconstruction-level selection only:

- CCQE efficiency for interactions within 6.1 m: $\epsilon_{\text{hit}} \epsilon_{\text{rec}} \simeq 39\%$. Fiducial volume only $\simeq (5/6.1)^3 \simeq 55\%$;
- CCQE purity: $\eta_{\text{CCQE}} \equiv \frac{N_{\text{CCQE}}}{N_{\text{all}}} \simeq 54\%$



Add event-level selection ($\text{numuCCQElike} > 0.14$):

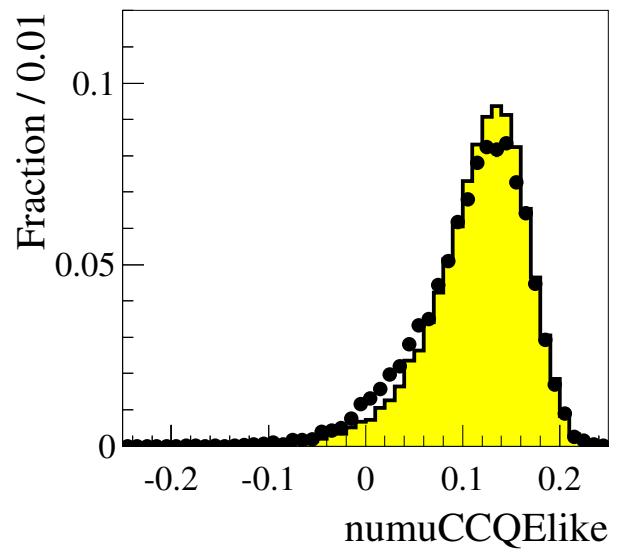
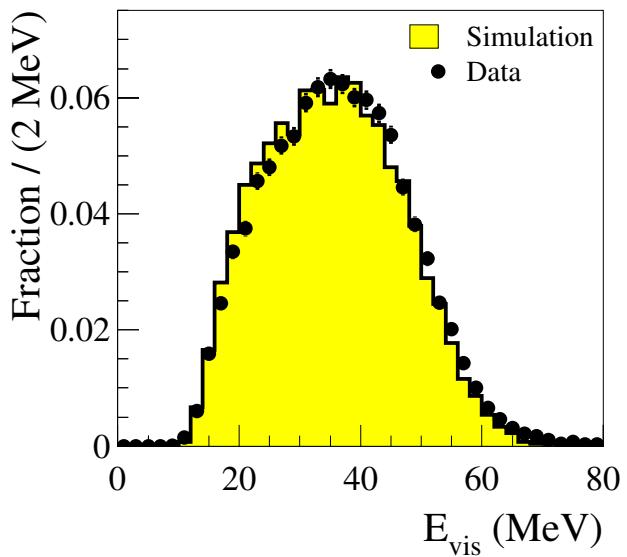
- CCQE efficiency: $\epsilon_{\text{Fisher}} \simeq 63\% \Rightarrow \epsilon_{\text{hit}} \epsilon_{\text{rec}} \epsilon_{\text{Fisher}} \simeq 25\%$
- CCQE purity: $\eta_{\text{CCQE}} \simeq 82\%$
- Irreducible non-CCQE background from events that *look like* CCQE, e.g. $\nu_\mu p \rightarrow \mu^- p \pi^+$ where π^+ is absorbed in nuclear environment
- CCQElike purity: $\eta_{\text{CCQElike}} \equiv \frac{N_{\text{CCQElike}}}{N_{\text{all}}} \simeq 89\%$



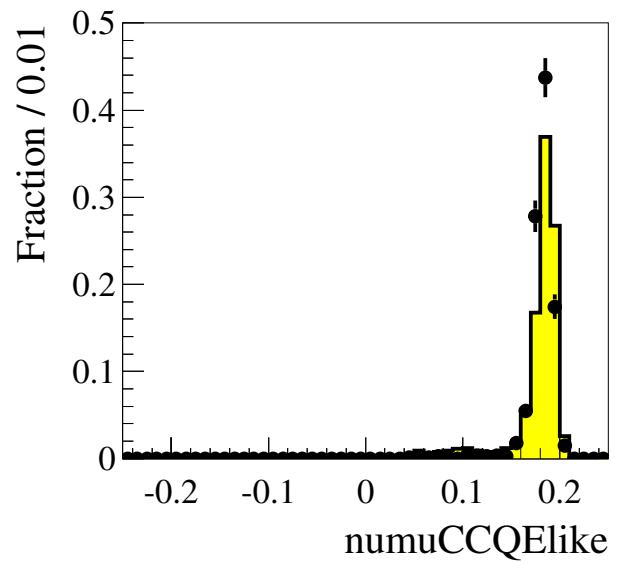
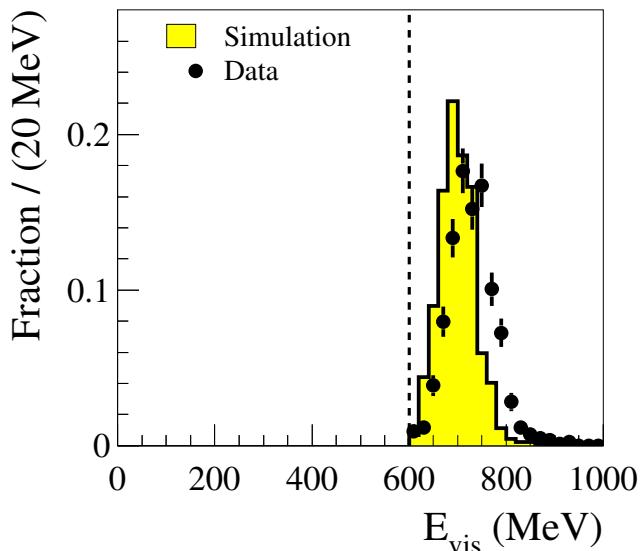
Using Calibration Samples for Validation

- Calibration samples used to validate energy reconstruction and CCQE selection
- Test detector response model. Do not depend on flux and cross-section predictions

Electron Calibration Sample

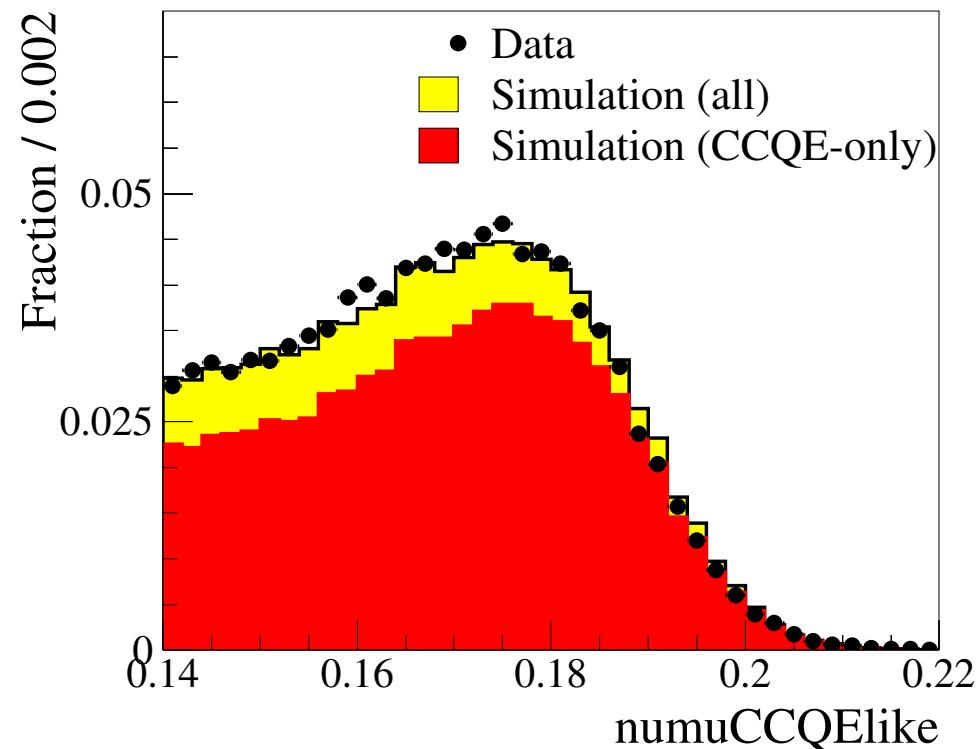


Muon Calibration Sample



The CCQE Sample Analyzed

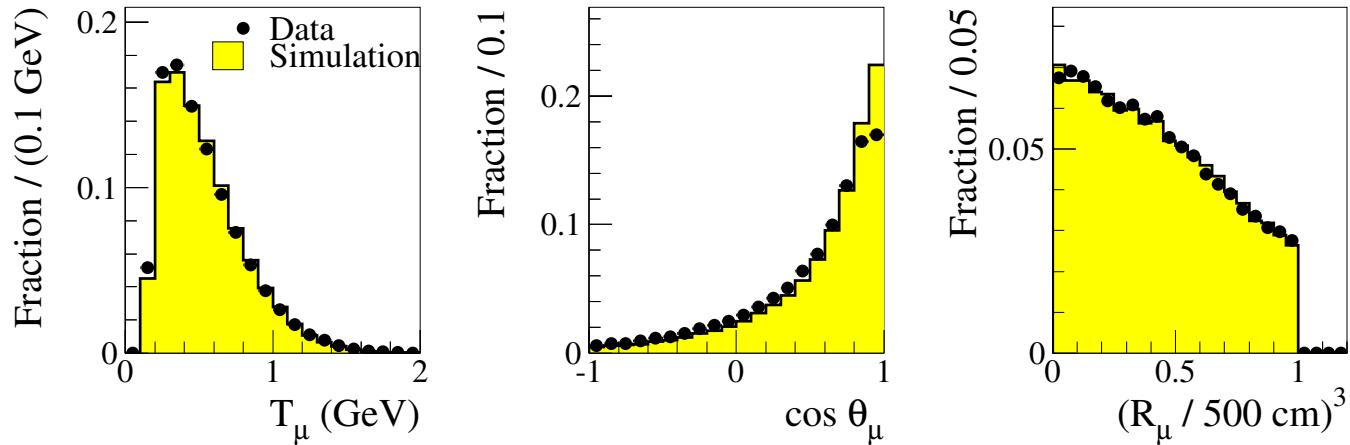
- Use neutrino data collected between December, 2002, and January, 2005
Number of protons on target: $N_{\text{pot}} = 1.9 \cdot 10^{20}$
- 55,824 CCQE neutrino candidates collected, requiring:
 - CCQE selection;
 - data of good quality (*e.g.* horn-on).
- Compare shapes of observed and predicted distributions
 \Rightarrow look for unsimulated new physics
- Observed CCQE identification well modelled by simulations



Muon and Neutrino Properties in $\nu_\mu n \rightarrow \mu^- p$ Interactions

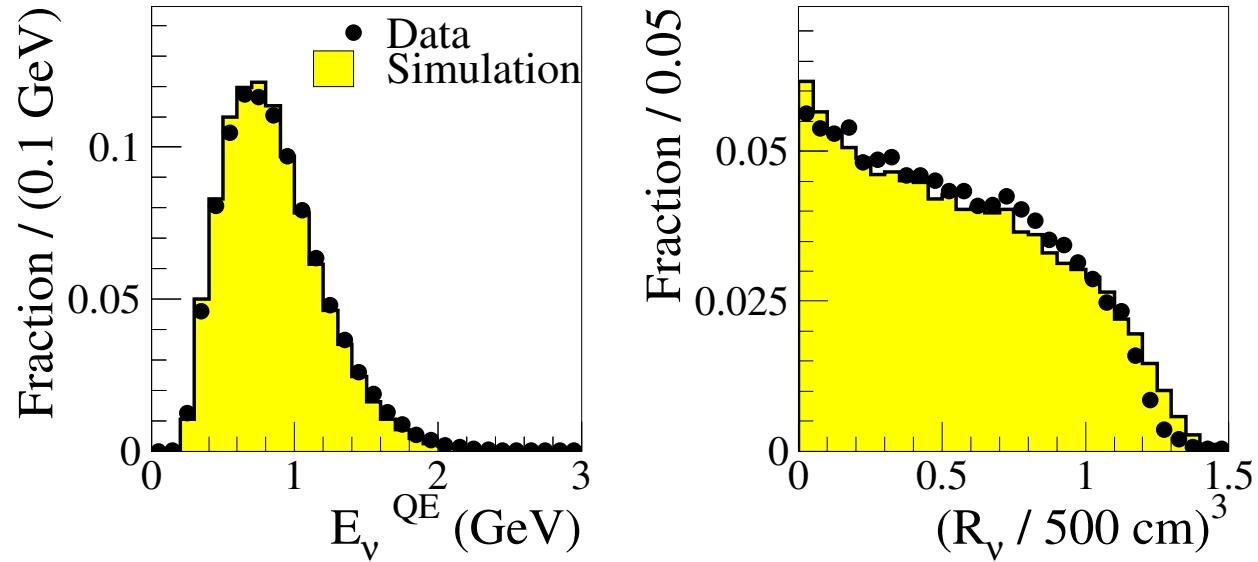
CCQE Muons:

- T_μ : muon kinetic energy
- θ_μ : angle between muon and neutrino directions
- R_μ : radial position of mean light emission point



CCQE Neutrinos:

- E_ν^{QE} : neutrino energy
- R_ν : radial position of neutrino interaction vertex
- Prediction assumes no neutrino oscillations

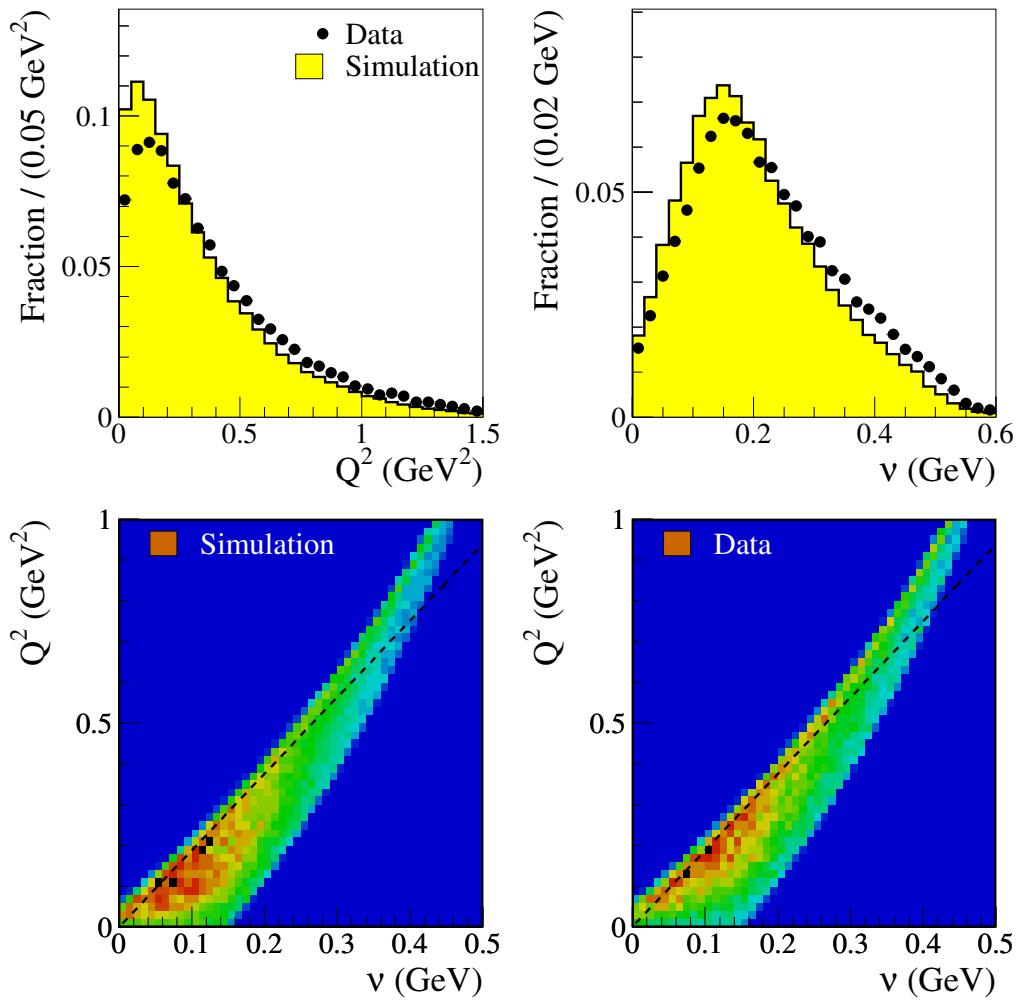


Properties of $\nu_\mu n \rightarrow \mu^- p$ Interactions

CCQE Kinematics:

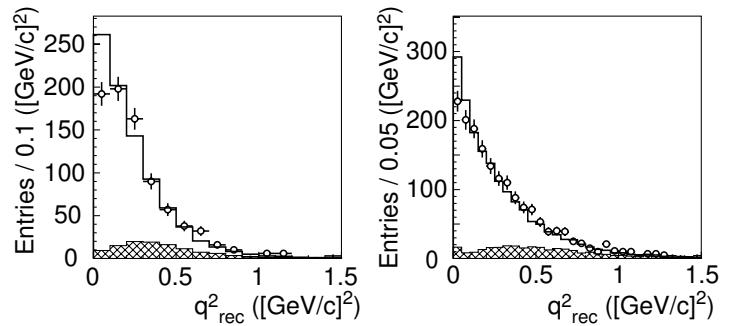
- $Q^2 \equiv -(p_\nu - p_\mu)^2$
- $\nu \equiv E_\nu - E_\mu$
- Dashed line is prediction for perfect detector, no nuclear effects:

$$Q^2 = 2m_N\nu$$



Rate suppression at $Q^2 \lesssim 0.15 \text{ GeV}^2 / \cos \theta_\mu \gtrsim 0.8$?

- Could be due to unsimulated nuclear effects
- Also seen by K2K experiment (hep-ex/0411038)



Computing the Sensitivity to Sterile Neutrinos via Muon Neutrino Disappearance

- Energy-shape analysis \Rightarrow look for energy-dependent distortions in the observed distribution, compared to predictions, by minimizing:

$$\chi^2(\Delta m^2, \sin^2 2\theta_{\mu\mu}, k) = \sum_{\alpha, \beta} (N_{\alpha}^{\text{obs}} - k N_{\alpha}^{\text{pred}})(M^{-1})_{\alpha\beta}(N_{\beta}^{\text{obs}} - k N_{\beta}^{\text{pred}})$$

where:

- $\Delta m^2, \sin^2 2\theta$: oscillation parameters, k : data/prediction yield ratio parameter
- $N_{\alpha}^{\text{pred}} = N_{\alpha}^{\text{pred}}(\Delta m^2, \sin^2 2\theta_{\mu\mu})$: predicted yield in reconstructed energy bin α
- N_{α}^{obs} : observed yield; $\sum_{\alpha} N_{\alpha}^{\text{obs}} \simeq 5.6 \cdot 10^4$
- $M_{\alpha\beta} = M_{\alpha\beta}^{\text{stat}} + M_{\alpha\beta}^{\text{flux}} + M_{\alpha\beta}^{\text{xsec}} + M_{\alpha\beta}^{\text{det}}$: matrix describing statistical errors, and systematic errors related to flux, cross-section, and detector response predictions
- Goodness-of-fit test of no-oscillation hypothesis: vary k , fix $\sin^2 2\theta = 0$
- Oscillation parameters estimation: minimize χ^2 by varying $\Delta m^2, \sin^2 2\theta, k$
- Sensitivity study \Leftrightarrow parameter estimation with: $N_{\alpha}^{\text{obs}} \equiv N_{\alpha}^{\text{pred}}(\sin^2 2\theta_{\mu\mu} = 0)$

Systematic Error Assumptions and Expected Sensitivity

- Impact of systematic uncertainties on energy shape dominates over statistics

Flux predictions:

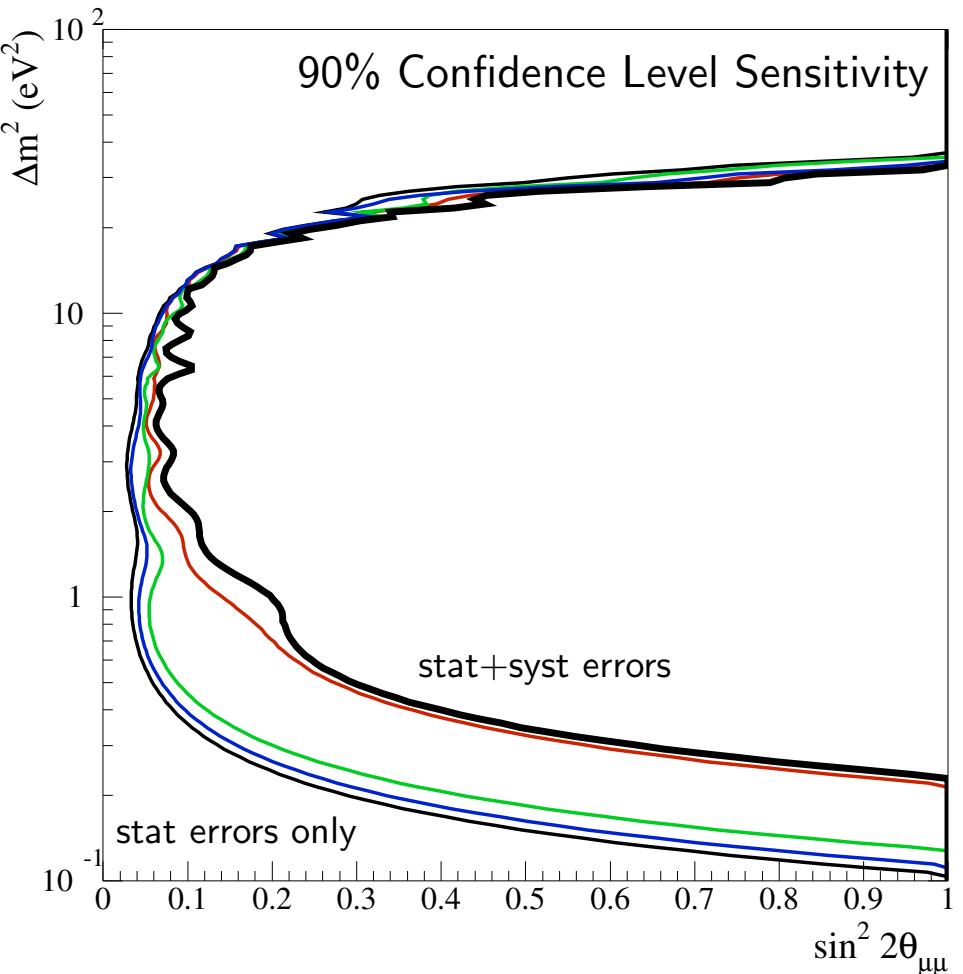
- π^+ production in $p + Be \rightarrow \pi^+ + X$ interactions: uncertainties on S-W parameters

Cross-section predictions:

- Nuclear effects: uncertainties on E_B , p_F
- CCQE form factors: uncertainty on m_A

Detector response:

- energy reconstruction: energy scale and non-linearity uncertainties estimated from muon calibration sample
- full detector response uncertainties, including effects on CCQE selection, still missing from analysis

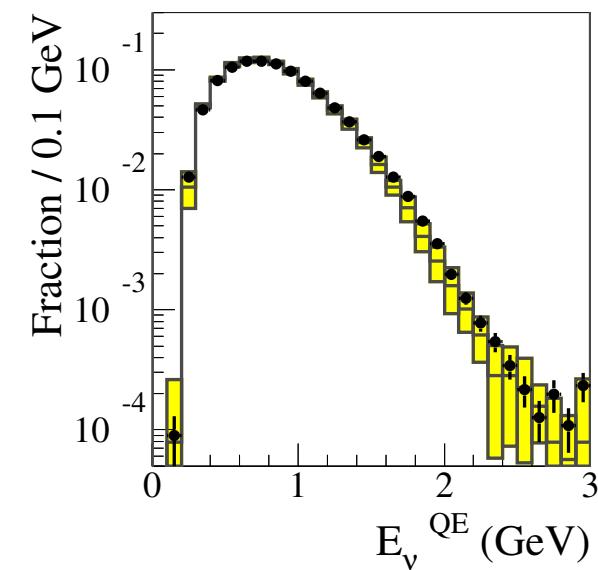
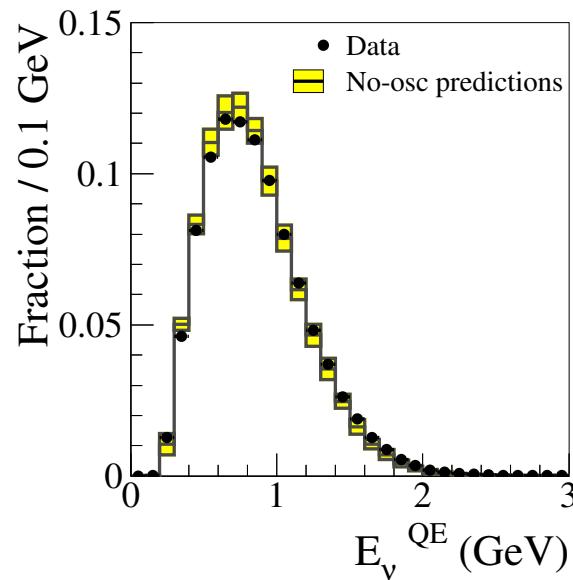


- Maximum Δm^2 range probed in energy-shape analysis: $0.1 \lesssim \Delta m^2 \lesssim 30 \text{ eV}^2$. Set by L/E distribution, statistics, energy resolution. Sensitivity to $\sin^2 2\theta_{\mu\mu} \gtrsim 0.1$

Comparing Observations with No-Oscillation Predictions

Neutrino Energy Shape:

- Boxes indicate current systematic uncertainty estimates
- Qualitative agreement between data / no-oscillation predictions

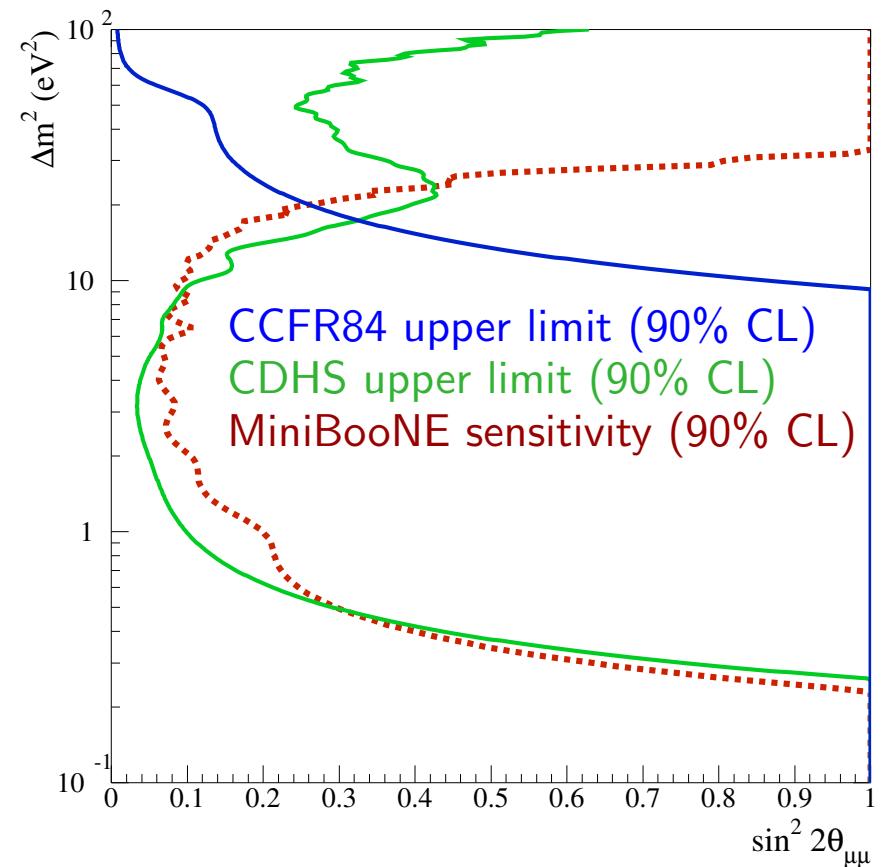


CCQE Rate Normalization:

- Flux+cross-section predictions: 17% normalization systematic uncertainty
- CCQE neutrinos-to-protons double ratio: $\frac{(N_{\text{CCQE}}/N_{\text{pot}})^{\text{obs}}}{(N_{\text{CCQE}}/N_{\text{pot}})^{\text{pred}}} = 1.60 \pm 0.17 !$
- No quantitative constraints on neutrino oscillations, because:
 - overall CCQE rate normalization not yet understood
 - full detector response systematic uncertainties still being evaluated

Toward Muon Neutrino Disappearance Results

- Compare MiniBooNE sensitivity to muon neutrino disappearance with existing upper limits, assuming that:
 - observed-to-predicted CCQE rate normalization ratio discrepancy due to currently unsimulated effect, independent of neutrino energy and interaction type (CCQE, CC π^+ , NC π^0 , NCE)
 - detector response systematic uncertainties affecting CCQE selection are negligible
- MiniBooNE sensitivity to $\nu_\mu \rightarrow \nu_\mu$ expected to be similar to best current limits
- HARP p-Be $\rightarrow \pi^+ + X$ results may improve sensitivity further
- Oscillation parameter regions probed by MiniBooNE include currently allowed sterile neutrino models (*e.g.* 3+1 and 3+2 models)
- Δm^2 measurement with $\simeq 20\%$ accuracy is possible, if $\nu_\mu \rightarrow \nu_s$ oscillations exist



Conclusions

Sterile neutrinos and oscillations:

- solar+atmospheric+LSND oscillations may point to the existence of light sterile neutrino species, and to active-to-sterile oscillations
- sterile neutrino models predict large muon neutrino disappearance, via $\nu_\mu \rightarrow \nu_s$

Ingredients for MiniBooNE muon neutrino disappearance search:

- External neutrino flux and cross-section predictions
- Selection of CCQE interactions, $\nu_\mu n \rightarrow \mu^- p$, and neutrino energy reconstruction

Preliminary look at CCQE interactions, and at disappearance sensitivity:

- qualitative agreement between data and predictions for no oscillations
- low- Q^2 and CCQE rate normalization puzzles
- potential to extend muon neutrino disappearance searches beyond current limits, and to confirm or refute sterile neutrino models

Outcome of This Thesis

Published Work:

- M. Sorel and J. M. Conrad, “*Supernova neutrinos and the LSND Evidence for Neutrino Oscillations,*” Phys. Rev. D **66**, 033009 (2002) [arXiv:hep-ph/0112214]
- M. Sorel, J. M. Conrad and M. Shaevitz, “*A combined analysis of short-baseline neutrino experiments in the (3+1) and (3+2) sterile neutrino oscillation hypotheses,*” Phys. Rev. D **70**, 073004 (2004) [arXiv:hep-ph/0305255]

Publications in Preparation ($\simeq 6$ months):

- A. Aguilar-Arevalo, V. Barger, J. M. Conrad, M. Shaevitz, M. Sorel, K. Whisnant, “*CP Violation in (3+2) Sterile Neutrino Models*”
- MiniBooNE Collaboration, “*The MiniBooNE Neutrino Focusing Horn*”
- MiniBooNE Collaboration, “*Neutrino Flux Predictions for the MiniBooNE Experiment*”
- MiniBooNE Collaboration, “*Search for Muon Neutrino Disappearance with the MiniBooNE Experiment*”

Thank You!

- MiniBooNE Collaboration



- Columbia Neutrino Group